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The chronostratigraphy of protoplanet Vesta

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ABSTRACT

In this paper we present a time-stratigraphic scheme and geologic time scale for the protoplanet Vesta, based on global geologic mapping and other analyses of NASA Dawn spacecraft data, complemented by insights gained from laboratory studies of howardite–eucrite–diogenite (HED) meteorites and geophysical modeling. On the basis of prominent impact structures and their associated deposits, we propose a time scale for Vesta that consists of four geologic time periods: Pre-Veneneian, Veneneian, Rheasilvian, and Marcian. The Pre-Veneneian Period covers the time from the formation of Vesta up to the Veneneia impact event, from 4.6 Ga to >2.1 Ga (using the asteroid flux-derived chronology system) or from 4.6 Ga to 3.7 Ga (under the lunar-derived chronology system). The Veneneian Period covers the time span between the Veneneia and Rheasilvia impact events, from >2.1 to 1 Ga (asteroid flux-derived chronology) or from 3.7 to 3.5 Ga (lunar-derived chronology), respectively. The Rheasilvian Period covers the time span between the Rheasilvia and Marcia impact events, and the Marcian Period covers the time between the Marcia impact event until the present. The age of the Marcia impact is still uncertain, but our current best estimates from crater counts of the ejecta blanket suggest an age between ~120 and 390 Ma, depending upon choice of chronology system used. Regardless, the Marcia impact represents the youngest major geologic event on Vesta. Our proposed four-period geologic time scale for Vesta is, to a first order, comparable to those developed for other airless terrestrial bodies.

1. Introduction

A goal of planetary geologic mapping is recognition of geologic units that are correlative with specific geologic time periods. For each of the terrestrial planets, geologic mapping has led to the development of a time-stratigraphic scheme and to a corresponding geologic time scale. These tools aid in comparative planetology, as the evolutionary path of a given body can be considered in the context of those of other planets.

This paper presents a time-stratigraphic scheme and geologic time scale for 4 Vesta, the second-most massive asteroid that has been described as the smallest terrestrial planet (Keil, 2002). We have used global and regional geologic maps and the results of other studies of Dawn mission data, including information gleaned from study of the howardite–eucrite–diogenite (HED) meteorites (McSween et al., 2011, and references therein), to produce this scheme and time scale. We then compare the proposed vestan time scale with those of other terrestrial bodies such as the Moon and Mercury.

2. Background

Geologic mapping is an investigative process that seeks to understand the evolution of planetary surfaces (Carr et al., 1976, 1984; Greeley and Carr, 1976; Wilhelms, 1990; Hansen, 2000; Tanaka et al., 2010). Geologic maps are thus tools that show the stratigraphic sequence of map units defined by geologic processes. Time-stratigraphic schemes can then be used to translate geologic maps into geologic timescales for planetary bodies. A geologic

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timescale clarifies the geologic evolution of the mapped body, which can then be compared with the corresponding timescales of other planets.

A time-stratigraphic (chronostratigraphic) scheme is a listing of the major time-rock units formed on a planet over its geologic history that remain visible today, in chronological order from oldest to youngest. Time-rock units serve to relate a geologic map's rock (lithostratigraphic) units (i.e., three-dimensional physical units that make up a body's crust) to its time units (i.e., the subdivisions of time during which the time-rock units were emplaced). The descriptors used to define the rock, time-rock, and time units depend upon the size or extent of the geologic unit on the planetary body. From large to small spatial scales, the rock unit descriptors are *supergroup*, *group*, *formation*, *member*, and *bed*, which correspond to the time-rock unit descriptors *eonathem*, *erathem*, *system*, *series*, and *stage*, and the corresponding time units *eon*, *era*, *period*, *epoch*, and *age*, respectively (Wilhelms, 1990). On planetary-scale geologic maps, formations are typically the distinctive rock units that can be individually mapped, which sometimes can be subdivided into members. Thus the corresponding time-rock units *system* and *series* (containing those rock units) and the time units *period* and *epoch* are conventionally used in planetary mapping.

For heavily cratered worlds, the largest impacts and their ejecta are convenient time-rock units, because they cover large areas of the surface and were formed instantaneously. An expansive ejecta deposit can be considered as a stratigraphic horizon that defines the onset of an event that builds a time-rock sequence. On the Moon, for example, rock units related to the Imbrium basin impact (collectively called the Fra Mauro Formation) are contained within the time-rock unit called the Lower Imbrian Series, which is correlated with a time unit called the Early Imbrian Epoch (Wilhelms, 1987, 1990). On Mercury, rock units related to the Caloris basin impact are contained within the time-rock unit called the Calorian System, which is correlated with a time unit called the Calorian Period (Spudis, 1985; Wilhelms, 1990). Because Vesta's surface is dominated by the products of impact cratering, we use prominent impact craters and their ejecta deposits to develop Vesta's chronostratigraphic system.

3. Data and methods

During the 14-month orbital mission of NASA's Dawn spacecraft, the geology of Vesta was investigated using a variety of techniques. For example, photogeologic, color-ratio imaging, and stereo image-based topographic analyses using monochrome and color data from Dawn's Framing Camera (FC: Reddy et al., 2012a, 2012b) were used in global and regional geologic mapping (Jaumann et al., 2012; Yingst et al., in press; Williams et al., in press-b, this issue). Application of crater statistical techniques were applied to mapped terrains to determine relative and absolute model ages of portions of the surface (Marchi et al., 2012a, 2012b, in press; O'Brien et al., 2014; Schmedemann et al., 2014). Hyperspectral and thermophysical analyses of multi-wavelength visible and near-infrared data from Dawn's Visible and Infrared Spectrometer (VIR: De Sanctis et al., 2012; Ammannito et al., 2013a), and correlation of geology with geochemical distributions derived from Dawn's Gamma Ray and Neutron Detector (GRaND: Prettyman et al., 2012, 2013; Yamashita et al., 2013), were used to provide information on the mineralogical and physical composition of surface materials. Finally, assessment of Vesta's gravity, mass distributions, and crustal thickness were obtained from Dawn's Radio Science experiment (Konopliv et al., 2013; Park et al., 2014; Raymond et al., 2013, 2014). In addition, Dawn compositional data were compared with the large body of petrologic, geochemical, and geochronologic studies of HED meteorites (e.g., Keil, 2002; McSween et al., 2011, and references therein), which have been demonstrated to have come from Vesta or its associated vestoid family (McSween et al., 2013a). Mathematical computer modeling of large impact events (e.g., Jutzi and Asphaug, 2011; Bowling et al., 2013) has also aided in interpretation of Dawn data.

We reviewed all of these studies, with a focus on geological mapping at global (Jaumann et al., 2012; Yingst et al., in press) and regional scales (Williams et al., in press-b, this issue, Introductory paper and papers therein). Our goal was to identify key geologic events recorded on the surface of Vesta, as recognized through mapping and other studies (e.g., Buczkowski et al., 2012; Bowling et al., 2013), and from them synthesize a time-stratigraphic scheme and geologic time scale.

4. Absolute ages

The Dawn Science Team has developed two independent approaches that use crater statistics to derive absolute cratering retention ages for the surface of Vesta: (a) extrapolation of the lunar-derived crater production and chronology functions (Neukum and Ivanov, 1994) to Vesta (Schmedemann et al., 2014); and (b) application to Vesta of crater production and chronology functions derived from models of asteroid belt dynamics (Marchi et al., 2012a, 2012b, 2013, in press; O'Brien et al., 2014). The lunar-derived production and chronology functions, which are tied to the radiometric ages of the Apollo samples returned from the Moon, have been applied to other terrestrial planets (Hartmann and Neukum, 2001) and to other asteroids (Neukum and Ivanov, 1994; Chapman et al., 1996a, 1996b; Ivanov et al., 2002; Marchi et al., 2012a). Although the extrapolation of the lunar chronology to other terrestrial planets has been commonly accepted since the early work of Shoemaker (1962a, 1962b) based on both a dynamical justification (see, for instance, the discussion in Marchi et al., 2013 for a recent application to Mercury) and observation of a common projectile population (Neukum and Ivanov, 1994; Ivanov et al., 2002), its extrapolation to the asteroid belt is questionable (Marchi et al., 2012a, 2012b; O'Brien et al., 2014) because it lacks a quantitative theoretical justification. However, crater distributions observed on asteroids show similarities to the crater distributions observed on the terrestrial planets, leading to the assumption that both types of body were impacted by the same projectile population and with a similar flux (Neukum and Ivanov, 1994; Ivanov et al., 2002; Schmedemann et al., 2014). Nevertheless, in recent years, our understanding of the main asteroid belt has greatly improved, both in terms of its past dynamical evolution and the current size–frequency distribution (e.g., Bottke et al., 2005; Morbidelli et al., 2010, 2012). These improvements allowed the Dawn Science Team to build both a "model" crater chronology (that is not calibrated on radiometric ages) for main belt asteroids that is consistent with the current models of main belt evolution (O'Brien et al., 2014) and a crater chronology for main belt asteroids that is derived from the radiometrically calibrated lunar chronology (Schmedemann et al., 2014).

The lunar-derived and asteroid flux-derived chronologies do not produce similar absolute model ages, for two primary reasons. First, the production and chronology functions differ in both methods (O'Brien et al.; 2014; Schmedemann et al., 2014). Therefore, even where functions of both chronology systems are applied to the *same* crater size–frequency distribution, they will produce different results. The discrepancy in the absolute ages derived from the two schemes depends on the crater size range investigated and the shape of the chronology curve. For example, for a heavily cratered, presumably older terrain (>~3 Ga), the asteroid-based chronology tends to give an age older than the lunar-based chronology. For presumably younger (<~3 Ga) terrains (based on accumulated impact craters) both chronology functions are virtually identical and differences in the production functions dominate, depending on whether the counted craters are larger or smaller than the reference diameter of 1 km, to which the chronology functions are calibrated. If crater diameters >1 km are used, the steeper lunar-like production function results in higher crater frequencies and older model ages compared with the asteroid flux-derived chronology, and vice versa: lower crater frequencies and younger model ages for crater diameters <1 km (Kneissl et al., this issue; Schmedemann et al., 2014).

Second, the two chronology systems have assessed different geologic terrains to derive ages for certain stratigraphic units. For example, the asteroid-based chronology derived an age for the Rheasilvia basin from a single large area using craters >3 km diameter superposed on the basin's floor (Marchi et al., 2012a, 2012b). More recently Marchi et al., in press analyzed proximal ejecta terrains finding similar conclusions. In contrast, the lunar-based chronology considered craters in a diameter range of 0.6–45 km superposed on nine areas (the top of the Rheasilvia central mound, the Rheasilvia ejecta blanket, and various resurfaced, cratered areas in the northern hemisphere) (Schmedemann et al., 2014). Thus, because of the differences in derived model ages from the two chronology systems, we report model ages from both methods, until such time as the correct crater-counting methodology for asteroids can be determined.

Most of the Vesta family asteroids (vestoids) are thought to have formed as a result of the Rheasilvia impact (e.g., Marzari et al., 1996; McSween et al., 2013b). The combined mass of the vestoids is consistent with (i.e., lower than) the amount of material estimated to have been excavated by the Rheasilvia and/or Veneneia impacts (Schenk et al., 2012; Moskovitz et al., 2008; Ivanov and Melosh, 2013), and the spectra of vestoids match those of Vesta (e.g., Binzel and Xu, 1993). Marzari et al. (1999) calculated that the observed steep size distribution of vestoids would have been reduced to match the background asteroid population if the Vesta family were older than ~1 Ga, and the tight clustering of vestoid orbital elements supports this age constraint (Nesvorny et al., 2008). The relative youth of the Vesta family asteroids is also consistent with a recent age estimate (Milani et al., in press) based on study of asteroid orbital dynamics. Conversely, other workers (Moskovitz et al., 2008; Ivanov and Melosh, 2013) suggest that there is an apparent deficiency in volume of the observed vestoids that is consistent with dynamical depletion and collisional grinding over ~3.5 Ga. Furthermore, dynamical analysis of basaltic main belt asteroids suggests a minimum age of 1 Ga under specific circumstances for the V-type asteroids separated from the main Vesta family (Nesvorny et al., 2008). More realistic assumptions imply a dynamical evolution over at least 1 Ga (Nesvorny, personal communication, 2013). Because of these conflicting studies, further work is required to better understand the spectral and positional attributes of the vestoids and whether they all could have formed from Vesta's largest impact basins.

The radiometric ages of HED meteorites are generally found to be >4.4 Ga, and likely reflect igneous crystallization or subsequent cooling through isotope blocking temperatures (McSween et al., 2011, and references therein). ^{40}Ar/^{39}Ar ages, ranging from 4.5 to ~3.5 Ga (Bogard, 2011) are an exception, and these ages are generally interpreted to correspond to impact events on Vesta (Bogard, 1995; Kennedy et al., 2013) from high collision speeds (Marchi et al., 2013). However, typical impact speeds among asteroids in the main belt (~5 km/s) are not expected to produce heating sufficient to reset ^{40}Ar/^{39}Ar ages. To overcome this problem, Marchi et al. (2013) proposed that the impact reset Ar–Ar ages are due to high impact speed collisions, in agreement with recent understanding of early Solar System evolution. There is no obvious isotopic disturbance associated with the Rheasilvia impact in the asteroid flux-derived model, which gives an age for that impact of ~1 Ga. Ejection of the vestoids in the Rheasilvia event would not be expected to reset ^{40}Ar/^{39}Ar ages, because that requires residence in a thermally insulated ejecta layer and probably a higher-then-average impact speed. This view has recently somewhat changed thanks to significant improvements in the measurement techniques. Recent work (Lindsey et al., 2014) report new Ar–Ar ages from single feldspar grains (instead of large aggregates of different grains) from the Kapoeta howardite, that coincide with the asteroid-flux age of ~1 Ga age of the Rheasilvia impact event. However, spectrally distinct material in the ejecta blanket of Rheasilvia (described as "orange material" by Le Corre et al. (2013) based on its appearance in color composite images) may represent impact melt produced by the Rheasilvia basin-forming event. Subsequent impacts that formed craters with diameters in excess of ~20 km (e.g., Oppia crater) may have been able to excavate such isotopically disturbed material and accelerate it to beyond escape velocity. However, so far there is no clear chemical evidence that these potentially impact-melt-related deposits are directly related to HED meteorites.

As for the Veneneia basin, craters superposed on its floor were largely affected by the formation of Rheasilvia. It is therefore likely that crater retention ages from the floor of Veneneia reflect the age of the Rheasilvia resurfacing event rather than the formation of Veneneia itself (Schenk et al., 2012; Schmedemann et al., 2014). It is conceivable that Veneneia may be responsible for one of the measured ^{40}Ar/^{39}Ar ages, but more work is needed to investigate this assertion.

In substantial contrast to the asteroid-flux model, the lunar-derived model dates the Rheasilvia and Veneneia impact events as ~3.5 Ga and ~3.7 Ga, respectively. These events are apparently recorded by ^{40}Ar/^{39}Ar peaks in the Bogard (2011) data; this is curious, as the Rheasilvia impact should not be recorded if it were a low-velocity impact. If both impacts occurred only ~200 Ma apart it may be that heat deposited by the Veneneia impact beneath its central peak left the ^{40}Ar/^{39}Ar isotopic system open until the Rheasilvia impact excavated large amounts of that material (Schmedemann et al., 2014 and references therein). However, impact melt pools tend to cool rapidly (Vaughan et al., 2013). Another explanation is that the Rheasilvia impact occurred at a high impact velocity, although this interpretation is contradicted by the lack of large amounts of impact melt. On excavation, the isotopic system would be closed and respective ^{40}Ar/^{39}Ar ages would correspond to the Rheasilvia event. Kennedy et al. (2013) derived ^{40}Ar/^{39}Ar ages of 4.5 Ga and 3.7 Ga, and suggested that either the Veneneia and Rheasilvia impacts could have occurred at 4.5 Ga and 3.7 Ga, respectively, or that the older age reflects magmatic cooling and that the younger age was produced by either the Veneneia or Rheasilvia impacts. It should be noted, however, that this conclusion does not take into account the effect of the impact speed, nor crucially the fact that ^{40}Ar/^{39}Ar ages younger than the Rheasilvia basin formation age are were thought unlikely because no significant younger crater is observed on Vesta. (For example, the volume of Marcia crater is negligible, by order of magnitudes, with respect to that of Rheasilvia).

5. Results

We present a time-stratigraphic scheme for Vesta (Table 1) that relates the global geologic map (rock) units (Fig. 1) identified from geologic mapping that are contained within a series of time-rock units, and their corresponding time units that define a geologic time scale (Fig. 2). When Dawn arrived at Vesta, it became clear

Table 1
Proposed time-stratigraphic scheme for Vesta. The correlation of Vesta's rock units, time-rock units, and time units is derived from geologic mapping and other Dawn data analyses (e.g., Jaumann et al., 2012; Buczkowski et al., 2012; Yingst et al., in press; Williams et al., in press-a, this issue).

Rock unit	Time-rock unit	Time unit
Marcia Formation: Crater wall and ejecta materials, mass wasting materials, bright and dark crater materials, undifferentiated crater materials, Tholus material	Marcian System	Marcian Period
Rheasilvia Formation: smooth, ridged and grooved, and mound terrains, Divalia Fossae formation, undifferentiated crater materials, Tholus material	Rheasilvian System	Rheasilvian Period
Saturnalia Fossae Formation	Veneneian System	Veneneian Period
Cratered highlands and plains, possibly Vestalia Terra	Pre-Veneneian System	Pre-Veneneian Period

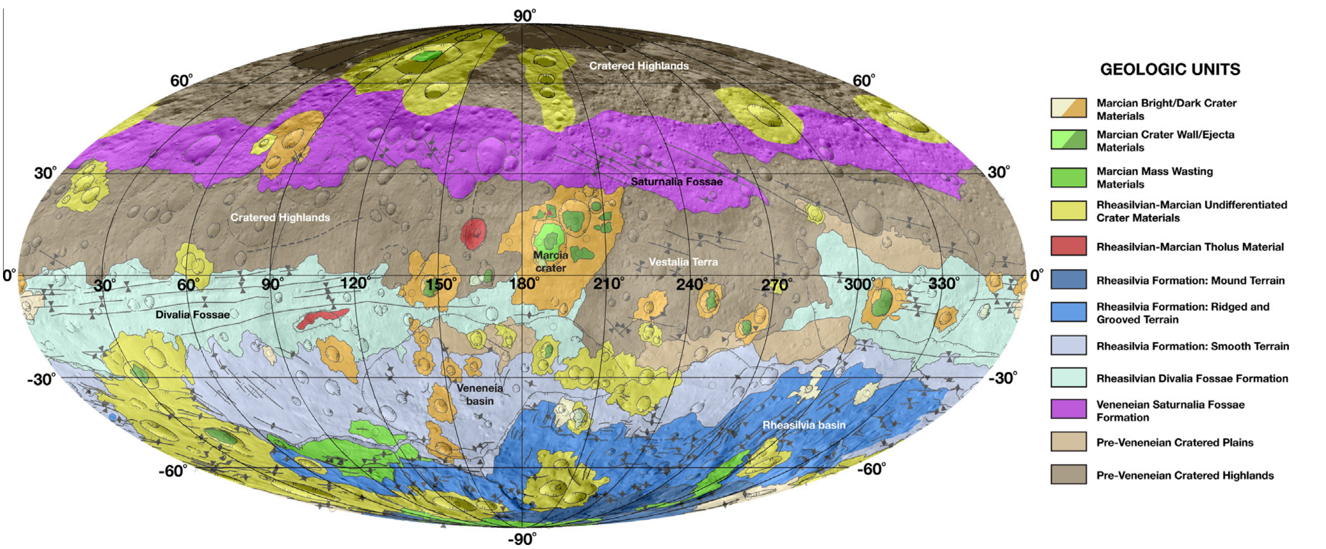

Fig. 1. Generalized global geologic map of Vesta, showing the spatial distribution of major types of materials, adapted from Yingst et al. (in press). The map is shown in a Mollweide projection, using east-positive longitudes, centered on 180°, Claudia coordinate system (Russell et al., 2012). This map is underlain by a Dawn Framing Camera High Altitude Mapping Orbit-2 image photomosaic.

rapidly, on the basis solely of crater abundances, that the oldest terrains are in the northern hemisphere (antipodal to the southern impact basins), the youngest terrain occurs in the floors of the south polar basins, and that the equatorial latitudes are more complex and probably intermediate in age (Marchi et al., 2012a, 2012b; Yingst et al., in press). Dawn images resolved two large impact structures in the south polar region, the older Veneneia basin (~400 km in diameter) superposed by the younger Rheasilvia basin (~500 km in diameter) (Schenk et al., 2012; Jaumann et al., 2012). The ejecta deposits from these two impact events are extensive; FC clear filter images show that the continuous ejecta field from Rheasilvia extends to equatorial latitudes (Schenk et al., 2012; Jaumann et al., 2012; Yingst et al., in press). However, the distribution of the Rheasilvia–Veneneia ejecta is not homogeneous in either extent or depth, and these deposits did not erase the largest (few tens of km diameter) craters (Schenk et al., 2012; Marchi et al., 2012a, 2012b). Additionally, FC color data (Reddy et al., 2012a, 2012b) and the GRaND global iron map (Yamashita et al., 2013) show a large lobe of apparent Rheasilvia ejecta extending across the Gegania and Lucaria quadrangles (Schaefer et al., 2014). There is also evidence that small (<5-km-diameter) lobes of either Rheasilvia or Veneneia ejecta extend well into the northern hemisphere (Williams et al., in press-a).

Global geologic mapping (Jaumann et al., 2012; Yingst et al., in press) identified two separate sets of prominent ridges and troughs, one set encircling much of Vesta's equatorial region (Divalia Fossae: see also Schaefer et al., 2014) and the other preserved in the heavily cratered northern terrain (Saturnalia Fossae). Structural analysis of these ridge-and-trough systems indicated that they are likely a tectonic response to the formation of the south polar basins: the Veneneia impact led to the formation of the Saturnalia Fossae, with the Rheasilvia impact leading to the Divalia Fossae (Jaumann et al., 2012; Buczkowski et al., 2012; Bowling et al., 2014). Consequently, crosscutting relationships of these structures can be used to assist in age dating. Crater counts (Table 2) on portions of the global geologic map units, including the Rheasilvia Formation (i.e., the Rheasilvia–Veneneia crater floor) as well as the Vestalia Terra topographic feature and other cratered highlands, provide cratering model ages for the Rheasilvia impact of ~3.5 Ga or ~1 Ga, and ages for the Veneneia impact of ~3.7 Ga or >2.1 Ga, using the lunar-derived and asteroid flux-derived chronologies, respectively (Marchi et al., 2012a, 2012b; Schmedemann et al., 2014). Despite the differences in absolute ages, and although there are uncertainties regarding whether the Divalia and Saturnalia Fossae terrains were fully reset by the formation of Rheasilvia and Veneneia, respectively, it is clear that these two large impact events had global effects, and thus delineate major periods of Vesta's geologic history.

The most heavily modified portions of Vesta's ancient crust include zones of heavily cratered terrain (Marchi et al., 2012a, 2012b, 2013; Schmedemann et al., 2014) in the northern hemisphere, including areas originally mapped within the Saturnalia Fossae Formation that are now mapped as cratered highlands (see Ruesch et al., 2014, this issue; Scully et al., 2014, this issue). Crater counts of these terrains indicate ages of 4.3–4.5 Ga for the asteroid-flux chronology model (O'Brien et al., 2014), or ~3.74 Ga using the lunar derived chronology model (Schmedemann et al., 2014). Additionally, geologic and geophysical evidence

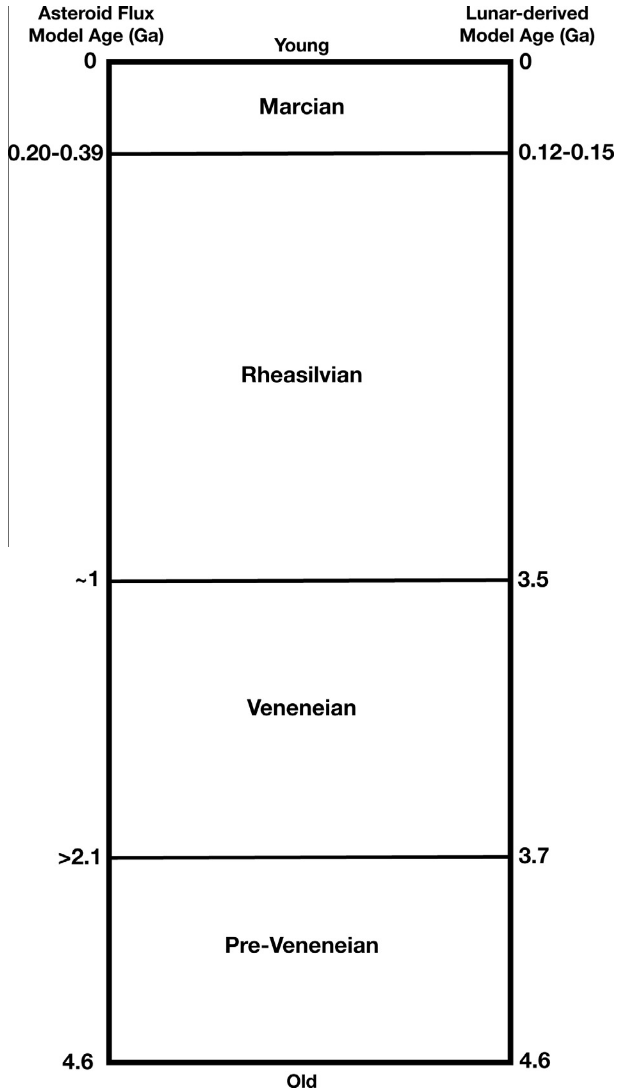

Fig. 2. Proposed geologic time scale for Vesta, including our proposed vestan time units. The age dates at left are cratering model ages derived from the asteroid flux-derived chronology function of O'Brien et al. (2014). The age dates at right are cratering model ages derived from the lunar-derived chronology system of Schmedemann et al. (2014). The black lines separate the different periods (see Tables 1–3), but note the different age scales for the respective chronology systems.

Table 2
Cratering model ages of Vesta's major impact events using the two chronology systems developed by the Dawn Science Team.

Unit name	Lunar-derived chronology Cratering model age (Ga)	Asteroid flux-derived chronology Cratering model age (Ga)
Rheasilvia impact	∼3.5[a]	1.0[b]
Veneneia impact	∼3.7[a]	>2.1[b]
Pre-Veneneian material (oldest crust)	∼4.0[a]	∼4.2–4.4[c]

[a] From Schmedemann et al. (in preparation).
[b] From Schenk et al. (2012).
[c] From Marchi et al. (in preparation).

(Buczkowski et al., in press; Raymond et al., 2013, 2014) suggest that Vestalia Terra is probably a large surviving fragment of Vesta's original crust, although superposed craters give younger ages for parts of Vestalia Terra because the Veneneia and Rheasilvia impacts obliterated preexisting craters. Nevertheless, it is clear from study of these geologic units that there must be crustal material exposed that pre-dates the Veneneia impact on Vesta, and that a Pre-Veneneian System and Pre-Veneneian Period must therefore be included as part of Vesta's geologic history.

The geologic units in and around the 68 × 58 km Marcia crater (10°N, 190°E) delineate the most recent large impact event on Vesta. It is not currently clear as to how to interpret some of the Marcia crater deposit ages, as some units in and around Marcia may have been modified by post-emplacement processes (Hiesinger et al., 2014). Moreover some age estimates do not consider the effect of variable mechanical properties of the vestan surface, which is required in order to facilitate global comparisons. At present the best crater counts of areas of the Marcia ejecta blanket (Table 3) give cratering model ages of ∼120–150 Ma or ∼220–390 Ma using the lunar-derived and asteroid flux-derived chronologies, respectively (Williams et al., in press-b, this issue). We use the ages derived from the ejecta deposits exterior to the crater to avoid possible post-impact emplacement processes on the crater floor. The units around Marcia represent the youngest regional geologic event on Vesta. The units associated with the Marcia impact event together make a set of related geologic units defined as the Marcia Formation (Williams et al., in press-b, this issue), which we propose as the base of Vesta's youngest system and period (Table 1).

6. Discussion

6.1. Other vestan features not included in the time-stratigraphic scheme

We considered whether other distinctive surface features should be included in the vestan time-stratigraphic scheme. For example, Dawn FC Clementine-type false color ratio images show unusual bright orange ejecta deposits surrounding the craters Oppia and Octavia (Reddy et al., 2012a; Le Corre et al., 2013). However, the ejecta around the 28-km-diameter crater Octavia, although spectrally distinctive, appear to only thinly mantle the underlying topography (Williams et al., in press-b, this issue). Despite both craters having these unusual diffuse surface mantles, neither Octavia nor Oppia (∼35-km-diameter) have produced any other noticeable regional effects (Garry et al., in preperation). Thus, these cratering events craters have not been included in the time-stratigraphic scheme.

We considered whether Vesta's youngest period should be restricted to rayed craters, by analogy with the Moon's Copernican Period or Mercury's Kuiperian Period. The young crater Marcia itself does not display any clear rays. Our analyses of Vesta's many (tens) smaller bright- and dark-rayed craters (Jaumann et al., 2014) has shown that they are very difficult to date with crater-counting statistics, because of complexities inherent to Vesta's surface that include slope effects, mass wasting processes, and modification by secondary craters (Schmedemann et al., 2014; Marchi et al., in press). Although we suspect that all of Vesta's rayed craters are younger than the estimated age of Marcia crater ejecta, and thus fall within the Marcian Period, we do not have sufficient data with which to define a separate epoch. Moreover the effects of space weathering on Vesta are different than on the Moon (Pieters et al., 2012), and it is unclear over what time span vestan crater rays would degrade due to these processes (cf., Hawke et al., 2004). Thus, we do not *de facto* equate Vesta's rayed craters with the Marcian Period.

6.2. Comparison of the vestan time scale to those of other terrestrial bodies

We can compare our proposed vestan geologic time scale (Fig. 3) with those of other terrestrial bodies. For the Moon, the

Table 3
Summary of cratering model ages of Marcia crater floor and ejecta areas using the two chronology systems developed by the Dawn Science Team. Refer to Supplemental online material Fig. S1 for crater count areas.

Unit name	Lunar-derived chronology			Asteroid flux-derived chronology			Additional data
	N(1) (km^{-2})	Cratering model age (Ma)	Fit diameter range (km)	N(1) (km^{-2})	Cratering model age (Ma)	Fit diameter range (km)	
Marcia ejecta blanket, area 5a	2.51×10^{-3}	123 ± 9.3	0.17–0.9 (170 craters)	7.18×10^{-3}	358 ± 22	0.14–1 (244 craters)	Area: 2.83×10^2 km, 282 craters counted
Marcia ejecta blanket, area 5b	2.82×10^{-3}	138 ± 56	0.45–0.8 (6 craters)	4.47×10^{-3}	220 ± 83	0.4–0.8 (7 craters)	Area: 1.84×10^2 km, 93 craters counted
Marcia ejecta blanket, area 5c	2.45×10^{-3}	120 ± 12	0.3–0.7 (52 craters)	5.89×10^{-3}	289 ± 27	0.25–0.6 (69 craters)	Area: 5.15×10^2 km, 148 craters counted
Marcia ejecta blanket, area 5d	3.03×10^{-3}	149 ± 16	0.25–0.7 (73 craters)	7.90×10^{-3}	388 ± 41	0.25–1 (77 craters)	Area: 4.27×10^2 km, 106 craters counted

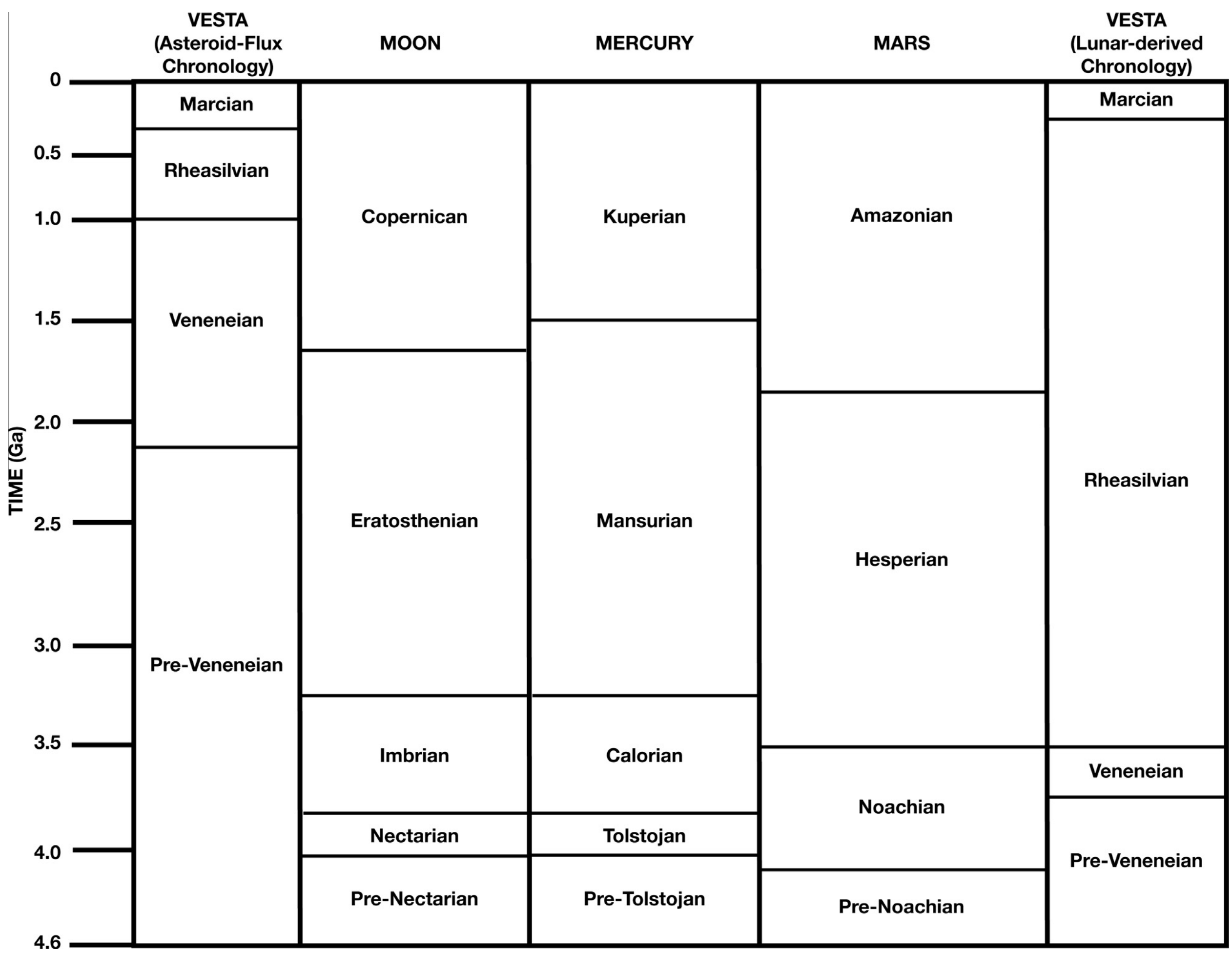

Fig. 3. The geologic time scale of Vesta, including our proposed time units, compared with those of the Moon, Mercury, and Mars. After Greeley (2013). The Vesta time scale using absolute model ages derived from asteroid flux-derived chronology (O'Brien et al., 2014) is at left, whereas the Vesta time scale using absolute model ages derived from lunar-derived chronology (Schmedemann et al., 2014) is at right.

Nectaris, Imbrium, and Orientale basin impacts define the early lunar periods, whereas the Tolstoj and Caloris impact basins define the earliest periods for Mercury. Pre-existing crust is therefore assigned to the Pre-Nectarian and Pre-Tolstojan Periods, respectively (Spudis, 1985; Wilhelms, 1990). In a similar manner, we recognize the importance of the Veneneia and Rheasilvia impact events and their corresponding global effects (as recognized by their relationships with the Divalia and Saturnalia Fossae: Jaumann et al., 2012; Buczkowski et al., 2012) on Vesta, and their utility in defining that body's major time units. At present, however, it is unclear whether the Rheasilvia–Veneneia time units are more akin to the Nectaris–Imbrium Periods on the Moon, which are separated by 200 Ma, or correspond to the Imbrium–Orientale Series, which respectively define the Early and Late Imbrium Epochs and are separated by 50 Ma. The lunar-derived chronology for Vesta (Schmedemann et al., 2014) indicates a separation of ~200 Ma between Veneneia and Rheasilvia, whereas the asteroid flux-derived chronology (Schenk et al., 2012; Marchi et al., 2012a, 2012b; O'Brien et al., 2014) suggest a >1 Ga separation. Because the separation is at least ~200 Ma, we chose to define the Veneneian and Rheasilvian as distinct periods in our timescale.

Although the timescales for the Moon and Mercury define their youngest periods (at least in part) on the survival times of rayed craters (i.e., the Copernican and Kuiperian Periods, respectively), both bodies are much closer to the Sun than Vesta and apparently have a similar surficial response to space weathering. Vesta has been noted to have a different response to space weathering than the Moon or Mercury, however, particularly in its lack of nanophase iron production in regolith (Pieters et al., 2012). Thus it is unclear for how long rays resulting from fresh, young craters on Vesta would survive. Although it may be that all rayed craters on Vesta are younger than Marcia crater, and thus should be included in the Marcian Period, the period itself cannot be defined on that basis.

7. Conclusions

Analysis of Dawn spacecraft data, including global and regional geologic mapping, coupled with study of HED meteorites and other studies, have enabled the development of a vestan time-stratigraphic scheme and geologic time scale. The four periods we propose tied to the major geologic events that have modified Vesta's surface, all of which are large impacts. The form of the vestan geologic time scale is, to first order, comparable to those developed for the Moon and Mercury, although our understanding of the duration of vestan rayed craters is not sufficient at this time to identify a period or epoch similar to the Copernican or Kuiperian Periods. Nevertheless, this vestan time-stratigraphic scheme and geologic time scale enables comparison of major vestan impact events to those on the other terrestrial bodies.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.icarus.2014.06.027.

References

Ammannito, E. et al., 2013a. Vestan lithologies mapped by the visual and infrared spectrometer on Dawn. Meteorit. Planet. Sci. 48, 2185–2198.

Binzel, R.P., Xu, S., 1993. Chips off Asteroid 4 Vesta: Evidence for the parent body of basaltic achondrite meteorites. Science 260, 186–191.

Bogard, D.D., 1995. Impact ages of meteorites: A synthesis. Meteoritics 30, 244.

Bogard, D.D., 2011. K–Ar ages of meteorites: Clues to parent-body thermal histories. Chem. Erde 71, 207–226.

Bottke, W.F., Durda, D.D., Nesvorný, D., Jedicke, R., Morbidelli, A., Vokrouhlický, D., Levison, H.F., 2005. Linking the collisional history of the main asteroid belt to its dynamical excitation and depletion. Icarus 179, 63–94.

Bowling, T.J. et al., 2013. Antipodal terrains created by the Rheasilvia basin forming impact on Asteroid 4 Vesta. J. Geophys. Res. 118, 1821–1834.

Bowling, T.J., Johnson, B.C., and Melosh, H.J., 2014. Formation of equatorial graben following the Rheasilvia impact on asteroid 4 Vesta. Vesta in the Light of Dawn Conference, abstract #2018, Lunar and Planetary Institute, Houston, Texas.

Buczkowski, D.L. et al., 2012. Large-scale troughs on Vesta: A signature of planetary tectonics. Geophys. Res. Lett. 39, L18205. http://dx.doi.org/10.1029/2012GL052959.

Buczkowski, D.L., Wyrick, D.Y., Yingst, R.A., Williams, D.A., Garry, W.B., Mest, S., Kneissl, T., Scully, J.E.C., Nathues, A., Le Corre, L., Reddy, V., De Sanctis, M.C., Ammanitto, E., Frigeri, A., Preusker, F., Roatsch, T., Raymond, C.A., Jaumann, R., Pieters, C.M., Russell, C.T., 2014. The geology of Vesta quadrangle Av-9 Numisia: Evaluating the unique geomorphology and physical properties of the Vestalia Terra plateau. Icarus, in press. http://dx.doi.org/10.1016/j.icarus.2014.03.035.

Carr, M.H., Wilhelms, D.E., Greeley, R., Guest, J.E., 1976. Stratigraphy and structural geology. In: Greeley, R., Carr, M.H. (Eds.), A Geological Basis for the Exploration of the Planets. NASA SP-417, pp. 13–32.

Carr, H.R., Saunders, R.S., Strom, R.G., Wilhelms, D.E., 1984. The Geology of the Terrestrial Planets. NASA-SP 469, pp. 317.

Chapman, C.R., Ryan, E.V., Merline, W.J., Neukum, G., Wagner, R., Thomas, P.C., Veverka, J., Sullivan, R.J., 1996a. Cratering on Ida. Icarus 120, 77–86.

Chapman, C.R., Veverka, J., Belton, M.J.S., Neukum, G., Morrison, D., 1996b. Cratering on Gaspra. Icarus 120, 231–245.

De Sanctis, M.C. et al., 2012. Spectroscopic characterization of mineralogy and its diversity across Vesta. Science 336, 697–700.

Greeley, R., 2013. Introduction to Planetary Geomorphology. Cambridge Univ. Press, Cambridge, UK, 238pp.

Greeley, R., Carr, M.H., 1976. A Geological Basis for the Exploration of the Planets. NASA SP-417, pp. 13–32.

Hansen, V.L., 2000. Geologic mapping of tectonic planets. Earth Planet. Sci. Lett. 176, 527–542.

Hartmann, W.K., Neukum, G., 2001. Cratering chronology and the evolution of Mars. Space Sci. Rev. 96, 165–194.

Hawke, B.R., Blewett, D.T., Lucey, P.G., Smith, G.A., Bell, J.F., Campbell, B.A., Robinson, M.S., 2004. The origin of lunar crater rays. Icarus 170, 1–16.

Hiesinger, H. et al., 2014. An in-depth study of Marcia crater, Vesta. Geophysical Research Abstracts 15 (EGU General Assembly). Abstract #EGU2014-10635.

Ivanov, B.A., Melosh, H.J., 2013. Two-dimensional numerical modeling of the Rheasilvia impact formation. J. Geophys. Res. (Planets) 118, 1545–1557.

Ivanov, B.A., Neukum, G., Bottke Jr., W.F., Hartmann, W.K., 2002. The comparison of size–frequency distributions of impact craters and asteroids and the planetary cratering rate. In: Bottke, W.F., Jr., Cellino, A., Paolicchi, P., Binzel, R.P. (Eds.), Asteroids III. University of Arizona Press, Tucson, pp. 9–101.

Jaumann, R. et al., 2012. Vesta's shape and morphology. Science 336, 687–690.

Jaumann, R., Nass, A., Otto, K., Krohn, K., Stephan,K., McCord, T.B., Williams, D.A., Raymond, C.A., Blewett, D.T., Hiesinger, H., Yingst, R.A., De Sanctis, M.C., Palomba, E., Roatsch, T., Matz, K.-D., Preusker, F., Scholten, F., Russell, C.T., 2014. The geological nature of dark material on Vesta and implications for the subsurface structure. Icarus, in press. http://dx.doi.org/10.1016/j.icarus.2014.04.035.

Jutzi, M., Asphaug, E., 2011. Mega-ejecta on asteroid Vesta. Geophys. Res. Lett. 38, L01102. http://dx.doi.org/10.1029/2010GL045517.

Keil, K., 2002. Geological history of Asteroid 4 Vesta: The "smallest terrestrial planet". In: Asteroids III. University of Arizona Press, Tucson, pp. 573–584.

Kennedy, T., Jourdan, F., Bevan, A.W.R., Gee, M.A.M., Frew, A., 2013. Impact history of the HED parent body(ies) clarified by $^{40}Ar/^{39}Ar$ ages of four HED meteorites and one anomalous basaltic achondrite. Geochim. Cosmochim. Acta 115, 162–182.

Kneissl, T., Schmedemann, N., Reddy, V., Williams, D.A., Walter, S., Neesemann, A., Michael, G., Jaumann, R., Krohn, K., Preusker, F., Roatsch, T., Le Corre, L., Nathues, A., Hoffmann, M., Schäfer, M., Buczkowski, D., Garry, W.B., Yingst, R.A., Mest, S., Russell, C.T., Raymond, C.A., this issue. Morphology and formation ages of mid-sized post-Rheasilvia craters – Geology of quadrangle Tuccia, Vesta. Icarus. http://dx.doi.org/10.1016/j.icarus.2014.02.012.

Konopliv, S.S., Asmar, S.W., Park, R.S., Bills, B.G., Centinello, F., Chamberlin, A.B., Ermakov, A., Gaskell, R.W., Rambaux, N., Raymond, C.A., Russell, C.T., Smith, D.E., Tricarico, P., Zuber, M.T., 2014. The Vesta gravity field, spin pole and rotation period, landmark positions, and ephemeria from the Dawn tracking and optical data. Icarus, in press. http://dx.doi.org/10.1016/j.icarus.2013.09.005.

Le Corre, L., Reddy, V., Schmedemann, N., Becker, K.J., O'Brien, D.P., Yamashita, N., Peplowski, P.N., Prettyman, T.H., Li, J.-Y., Cloutis, E.A., Denevi, B.W., Kneissl, T., Palmer, E., Gaskell, R.W., Nathues, A., Gaffey, M.J., Mittlefehldt, D.W., Garry, W.B., Sierks, H., Russell, C.T., Raymond, C.A., De Sanctis, M.C., Ammanito, E., 2013. Olivine or impact melt: Nature of the "Orange" material on Vesta from Dawn. Icarus 226, 1568–1594.

Lindsey, F.N., Delaney, J.S., Turrin, B.D., Herzog, G.F., Park, J., Swisher, C.C., 2014. Component chronology of Kapoeta: Ar–Ar systematics. Lunar Planet. Sci. 45. Abstract #1969.

Marchi, S. et al., 2012a. The cratering history of Asteroid (21) Lutetia. Planet. Space Sci. 66, 87–95.

Marchi, S. et al., 2012b. The violent collisional history of Asteroid 4 Vesta. Science 336, 690–694.

Marchi, S. et al., 2013. High velocity collisions from the lunar cataclysm recorded in asteroidal meteorites. Nat. Geosci. 6, 303–307.

Marchi, S. et al., 2014. Small crater populations on Vesta. Planet. Space Sci., in press. http://dx.doi.org/10.1016/j.pss.2013.05.005.

Marzari, F., Cellino, A., Davis, D.R., Farinella, P., Zappala, V., Vanzani, V., 1996. Origin and evolution of the Vesta asteroid family. Astron. Astrophys. 316, 248–262.

Marzari, F., Farinella, P., Davis, D.R., 1999. Origin, aging, and death of asteroid families. Icarus 142, 63–77.

McSween, H.Y., Mittlefehldt, D.W., Beck, A.W., Mayne, R.G., McCoy, T.J., 2011. HED meteorites and their relationship to the geology of Vesta and the Dawn mission. Space Sci. Rev. 163, 141–174.

McSween, H.Y. et al., 2013a. Dawn; the Vesta-HED connection; and the geologic context for eucrites, diogenites, and howardites. Meteorit. Planet. Sci. 48, 2090–2104.
McSween, H.Y. et al., 2013b. Composition of the Rheasilvia basin, a window into Vesta's interior. J. Geophys. Res. 188, 335–346.
Milani, A., Cellino, A., Knezevic, Z., Novakovic, B., Spoto, F., Paolicchi, P., 2014. Asteroid families classification: Exploiting very large data sets. Icarus, in press. ArXiv e-prints arXiv:1312.7702.
Morbidelli, A., Marchi, S., Bottke, W.F., Kring, D.A., 2012. A sawtooth-like timeline for the first billion years of lunar bombardment. Earth Planet. Sci. Lett. 355, 144–151.
Moskovitz, N.A., Jedicke, R., Gaidos, E., Willman, M., Nesvorný, D., Fevig, R., Ivezić, Ž., 2008. The distribution of basaltic asteroids in the main belt. Icarus 198, 77–90.
Nesvorny, D., Roig, F., Gladman, B., Lazzaro, D., Carruba, V., Mothe-Diniz, T., 2008. Fugitives from the Vesta family. Icarus 193, 85–95.
Neukum, G., Ivanov, B.A., 1994. Crater size distributions and impact probabilities on Earth from lunar, terrestrial-planet, and asteroid cratering data. In: Gehrels, Tom, Matthews, M.S., Schumann, A. (Eds.), Hazards due to Comets and Asteroids, Space Science Series. University of Arizona Press, Tucson, AZ, p. 359.
O'Brien, D.P. et al., 2014. The impact history of Vesta. In: Vesta in the Light of Dawn Conference. Lunar and Planetary Institute, Houston. Abstract #2049.
Park, R.S., Konopliv, A.S., Asmar, S.W., Bills, B.G., Gaskell, R.W., Raymond, C.A., Smith, D.E., Toplis, M.J., Zuber, M.T., 2014. Gravity field expansion in ellipsoidal harmonic and polyhedral internal representations applied to Vesta. Icarus, in press. http://dx.doi.org/10.1016/j.icarus.2013.12.005.
Pieters, C.M. et al., 2012. Distinctive space weathering on Vesta from regolith mixing processes. Nature 491, 79–82.
Prettyman, T.H. et al., 2012. Elemental mapping by Dawn reveals exogenic H in Vesta's regolith. Science 338, 242–246.
Prettyman, T.H. et al., 2013. Neutron absorption constraints on the composition of 4 Vesta. Meteorit. Planet. Sci. 48, 2211–2236.
Raymond, C.A. et al., 2013. The crust and mantle of Vesta's southern hemisphere. EPSC Abstracts, vol. 8. Abstract #EPSC2013-1002.
Raymond, C.A. et al., 2014. Constraints on Vesta's interior evolution from Dawn geophysical data. In: Vesta in the Light of Dawn Conference. Lunar and Planetary Institute, Houston. Abstract #2051.
Reddy, V. et al., 2012a. Color and albedo heterogeneity of Vesta from Dawn. Science 336, 700–704.
Reddy, V. et al., 2012b. Delivery of dark material to Vesta via carbonaceous chondritic impacts. Icarus 221, 544–559.
Ruesch, O., Hiesinger, H., Blewett, D.T., Scully, J., Buczkowski, D., Williams, D.A., Yingst, R.A., Russell, C.T., Raymond, C.A., 2014. Geologic map of the northern hemisphere of Vesta based on Dawn FC images. Icarus. http://dx.doi.org/10.1016/j.icarus.2014.01.035.
Russell, C.T. et al., 2012. Dawn at Vesta: Testing the protoplanetary paradigm. Science 336, 684–686.
Schaefer, M., L. Le Corre, A., Nathues, D.W., Mittlefehldt, D.L., Buczkowski, D.A., Williams, M., Hoffmann, T., Kneissl, G.S., Thanjam, V., Reddy, N., Schmedemann, J.E.C., Scully, T., Schaefer, J.-Y., Li, W.B., Garry, K., Krohn, R.A., Yingst, R,. Gaskell, C.T., Russell, 2014. Imprint of the Rheasilvia impact on Vesta – Geologic mapping of quadrangles Gegania and Lucaria. Icarus, in press. http://dx.doi.org/j.icarus.2014.06.026.
Schenk, P.M. et al., 2012. The geologically recent giant impact basins at Vesta's south pole. Science 336, 694–697.
Schmedemann, N. et al., 2014. The cratering record, chronology and surface ages of (4) Vesta in comparison to smaller asteroids and the ages of HED meteorites. Planet. Space Sci. http://dx.doi.org/10.1016/j.pss.2014.04.004.
Scully, J.E.C. et al., 2014. Vestan gullies and their formation mechanisms. In: Vesta in the Light of Dawn Conference. Lunar and Planetary Institute, Houston. Abstract #2001.
Scully, J.E.C., Yin, A., Russell, C.T., Buczkowski, D.L., Williams, D.A., Blewett, D.T., Ruesch, O., Hiesinger, H., Mercer, C.M., Le Corre, L., Garry, W.B., Yingst, R.A., Jaumann, R., Roatsch, T., Preusker, F., Gaskell, R.W., Schröder, S.E., Ammannito, E., Pieters, C.M., Raymond, C.A., the Dawn Science Team, this issue. Saturnalia Fossa group of fossae and additional structures in Vesta's northern hemisphere. Icarus. http://dx.doi.org/10.1016/j.icarus.2014.01.013.
Shoemaker, E.M., 1962a. Exploration of the Moon's surface. Am. Sci. 50, 99–130.
Shoemaker, E.M., 1962b. Interpretation of lunar craters. In: Kopal, Z. (Ed.), Physics and Astronomy of the Moon. Academic Press, pp. 283–359.
Spudis, P.D., 1985. A mercurian chronostratigraphic classification. In: Rep. Planet. Geol. Geophys. Prog. – 1984. NASA Tech. Mem. 87563, pp. 595–597.
Tanaka, K.L. et al., 2010. Planetary Geologic Mapping Handbook. <http://astrogeology.usgs.gov/Projects/PlanetaryMapping/>.
Vaughan, W.M., Head, J.W., Wilson, L., Hess, P.C., 2013. Geology and petrology of enormous volumes of impact melt on the Moon: A case study of the Orientale basin impact melt sea. Icarus 223, 749–765.
Wilhelms, D.E., 1987. The geologic history of the Moon. U.S. Geol. Surv. Prof. Pap. 1348. 302pp.
Wilhelms, D.E., 1990. Geologic mapping. In: Greeley, R., Batson, R.M. (Eds.), Planetary Mapping. Cambridge University Press, Cambridge, UK, pp. 208–260.
Williams, D.A. et al., 2013. Lobate and flow-like features on asteroid Vesta. Planet. Space Sci., in press-a. http://dx.doi.org/10.1016/j.pss.2013.06.017.
Williams, D.A., Denevi, B.W., Mittlefehldt, D.W., Mest, S.C., Schenk, P.M., Yingst, R.A., Buczkowski, D.L., Scully, J.E.C., Garry, W.B., McCord, T.B., Combe, J.-Ph., Jaumann, R., Pieters, C.M., Nathues, A., Le Corre, L., Hoffmann, M., Reddy, V., Roatsch, T., Preusker, F., Marchi, S., Kneissl, T., Schmedemann, N., Neukum, G., Hiesinger, H., De Sanctis, M.C., Ammannito, E., Frigeri, A., Prettyman, T.H., Russell, C.T., Raymond, C.A., and the Dawn Science Team, 2014. The geology of the Marcia quadrangle of asteroid Vesta: Assessing the effects of large, young craters. Icarus, in press-b. http://dx.doi.org/10.1016/j.icarus.2014.01.033.
Williams, D.A., Yingst, R.A., Garry, W.B., 2014. Introduction: The geologic mapping of Vesta. Icarus, this issue. http://dx.doi.org/10.1016/j.icarus.2014.03.001.
Yamashita, N. et al., 2013. Distribution of iron on Vesta. Meteorit. Planet. Sci. 48 (11), 2237–2251.
Yingst, R.A. et al., 2014. Geologic mapping of Vesta. Planet. Space Sci., in press. http://dx.doi.org/10.1016/j.pss.2013.12.014.